

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property  
Organization  
International Bureau



10/533248



(43) International Publication Date  
13 May 2004 (13.05.2004)

PCT

(10) International Publication Number  
**WO 2004/040690 A2**

- (51) International Patent Classification<sup>7</sup>: **H01Q**
- (21) International Application Number:  
PCT/US2003/034414
- (22) International Filing Date: 29 October 2003 (29.10.2003)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:  
60/422,277 29 October 2002 (29.10.2002) US
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(81) Designated States (*national*): AE, AG, AL, AM, AT, AU,  
AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU,  
CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH,  
GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC,  
LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW,  
MX, MZ, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC,  
SD, SE, SG, SK, SI, SY, TJ, TM, TN, TR, TT, TZ, UA,  
UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

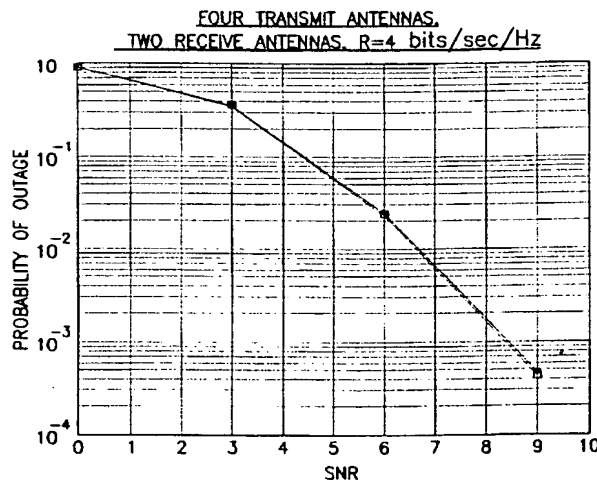
(84) Designated States (*regional*): ARIPO patent (GH, GM,  
KE, LS, MW, MZ, SD, SI, SZ, TZ, UG, ZM, ZW),  
Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM),  
European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE,  
ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, RO,  
SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM,  
GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— without international search report and to be republished  
upon receipt of that report

[Continued on next page]

(54) Title: LOW COMPLEXITY BEAMFORMERS FOR MULTIPLE TRANSMIT AND RECEIVE ANTENNAS



— SPATIAL WATER-FILLING WITH PERFECT CSIT  
— POWER ALLOCATION QUANTIZED TO 2 BITS

(57) Abstract: Beamforming systems having a few bits of channel state information fed back to the transmitter benefit from low complexity decoding structures and performance gains compared with systems that do not have channel state feedback. Both low rank and higher rank systems are implemented. Substantial design effort may be avoided by following a method of using functions formulated for space-time systems with the change that the channel coherence time is equated to the number of transmit antennas and the number of antennas in the space-time formulation is fixed at one.

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*For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.*

## Low Complexity Beamformers for Multiple Transmit and Receive Antennas

### TECHNICAL FIELD

The field of the invention is telecommunications, in particular antenna systems for cellular systems.

### BACKGROUND OF THE INVENTION

Various beamforming schemes for wireless systems equipped with multiple transmit and multiple receive antennas are known in the art. At present, space time coding schemes are currently proposed for multiple antenna systems.

Figure 1, taken from US Patent 6,584,302, assigned to the assignee hereof, presents a transceiver that has a group of antenna elements 200-204 for transmitting and receiving. The transceiver is usually a base station but it can also be a subscriber equipment. The antenna with several elements can be an antenna array or some other kind of cluster of antenna elements. Referring to receiver 260, each signal received from each antenna 200-204 enters RF-means 206-210 that convert the radio frequency signal to baseband signals in a known manner. The signals are digitized in A/D-converters 212-216. The digital baseband signals are multiplied by coefficients  $W_1 - W_M$  that form the shape of the beam of the antenna in multipliers 218-222. The coefficients  $W_1 - W_M$  are digital complex numbers. The receiver searches for the values of the coefficients  $W_1 - W_M$  that produce the best reception. Antenna responses are calculated in an antenna response unit 224 for each antenna element. The antenna responses are ranked and a subset of the set of the antenna responses is selected in rank and select unit 226.

A response of an antenna element is similar to an impulse response and is calculated

1 by using correlation. In the correlation a known pseudo-random spreading code is  
2 correlated with the received signal  $L$  times.  $L$  is the number of paths of the multipath  
3 propagated signal. After calculating one correlation value the spreading code is  
4 shifted by a time difference  $\Delta T$ , which can be the same as the duration of a chip.

5  
6 In the transmitter 262 the subset comprising at least one antenna response is fed to a  
7 coefficient unit 230 that calculates the coefficients  $a_1 - a_M$  for each antenna element  
8 200-204 transmitting a signal. The signal to be transmitted is multiplied by the  
9 coefficients using the multipliers 232-236. The signal weighted by the coefficients  $a_1$   
10  $-a_M$  is then converted to an analog signal by D/A-converters 238-242. After that, the  
11 analog signals are converted to radio frequency signals in RF-means 244-248 and the  
12 radio frequency signals are transmitted by the antenna elements 200-204.

13  
14 Low receiver complexity is one of the important design goals for downlink  
15 transmission where the handset (receiver) is constrained in its computational  
16 abilities.

17  
18 It is well known that channel state information at the transmitter can enhance the  
19 system performance significantly. However, in practical systems, only partial  
20 channel information may be available at the transmitter due to the limited nature of  
21 the feedback resources

22  
23 Hence, it is important to design feedback based transmission schemes for the cases  
24 where partial channel information is available at the transmitter. Transmission  
25 schemes for single receive antenna systems utilizing quantized channel information  
26 have been developed, but are not satisfactory.

27  
28  
29 SUMMARY OF THE INVENTION  
30

1  
2 The invention relates to a design criterion and beamformer constructions, which  
3 make use of finite rate feedback in the system.

4  
5 A feature of the invention is a beamforming scheme for wireless systems equipped  
6 with multiple transmit and multiple receive antennas.

7  
8 Another feature of the invention is the use of mathematical formalism originally  
9 developed for unitary space-time constellations for a beamformer.

10  
11 Another feature of the invention is the application of a beamformer construction that  
12 is equivalent to a spatial water-filling solution.

### 13 14 15 BRIEF DESCRIPTION OF THE DRAWING

16  
17 Figure 1 illustrates in block diagram form a multiple antenna system according to the  
18 prior art.

19  
20 Figures 2 - 6 illustrate performance of various configurations.

### 21 22 23 BEST MODE OF CARRYING OUT THE INVENTION

24  
25  
26  
27 The beamforming schemes presented in this disclosure result in improved  
28 performance at provably lower computational complexity compared to the space  
29 time coding schemes currently proposed for multiple antenna systems. Low receiver  
30 complexity is one of the important design goals for downlink transmission where the  
31 handset (receiver) is constrained in its computational abilities.

32  
33 It is well known that channel state information at the transmitter can enhance the  
34 system performance significantly. However, in practical systems, only partial  
35 channel information may be available at the transmitter due to the limited nature of  
36 the feedback resources. Hence, it is important to design feedback based transmission

1 schemes for the cases where partial channel information is available at the  
2 transmitter. Transmission schemes for single receive antenna systems utilizing  
3 quantized channel information have been developed.

4 In this work, we present a design criterion and beamformer constructions which  
5 make use of finite rate feedback in the system. In the first part of this disclosure, we  
6 present a unit rank beamforming strategy for multiple transmit and multiple receive  
7 antenna systems. In the second part, we present an algorithm to extend the  
8 beamformer codebook constructions to mimic a spatial water-filling solution with a  
9 finite number of feedback bits. We will show that both the schemes result in better  
10 performance at lower decoding complexity compared to space time coding. In  
11 particular, we can show that unit rank beamforming schemes are useful when the  
12 transmission rate is small. In fact, we can show that the unit rank beamforming  
13 schemes result in significant performance gains over space time coding schemes  
14 when  $2^{R/r}/t < 1$ , where  $R$  is the rate of transmission in bits/sec/Hz,  $r$  is the number of  
15 receive antennas and  $t$  is the number of transmit antennas. When this condition for  
16 unit rank beamforming is not met, i.e., for higher transmission rates, we propose  
17 higher rank beamforming schemes based on the spatial water-filling algorithm, using  
18 finite rate feedback.

19  
20 Consider a multiple antenna system with  $t$  transmit antennas and  $r$  receive antennas,  
21 such as that illustrated in Figure 1. Let us suppose that we wish to transmit at a  
22 spectral efficiency of  $R$  bits/sec/Hz. We denote the  $t \times 1$  transmitted vector by  $X$   
23 while the  $r \times 1$  received vector is denoted by  $Y$ . The additive white noise vector is  
24 denoted by  $N$  while the frequency non-selective Rayleigh fading channel between  
25 the transmit antennas and the receive antennas is given by the  
26  $r \times t$  matrix  $H$ . With this notation, the received signal  $Y$  can be expressed as  
$$Y=HX + N. \quad (1)$$

1 The channel fading is assumed to be quasi-static over time; i.e., the channel remains  
2 constant within a frame while the channel realization is independent from frame to  
3 frame. We assume that the channel is known perfectly at the receiver. In practice,  
4 good channel estimates can be obtained at the receiver by employing preamble based  
5 training in the system. We also assume the existence of an error-free feedback  
6 channel from the receiver to the transmitter which carries B bits every frame. For  
7 simplicity, power adjustment over time; (i.e., temporal power control) is not  
8 performed.

9  
10 We will first discuss unit rank beamforming schemes and analyze their performance.  
11 Unit rank beamforming schemes are optimal in the sense of minimizing outage  
12 probability in the important case when the number of receive antennas is restricted to  
13 1. Further, we have shown that unit rank beamforming with multiple receive  
14 antennas is optimal in the sense of minimizing the pair-wise codeword error  
15 probability. Additionally, unit rank beamforming schemes result in simple decoding  
16 structures with low computational complexity.

17  
18 We have shown that transmission along the dominant eigenvector of the channel  
19 minimizes the pairwise codeword error probability in the system. It has also been  
20 shown that the transmission along the dominant eigenvector of the channel  
21 maximizes received SNR while resulting in maximum diversity. We refer to this  
22 transmission strategy as the unit rank beamforming scheme.

23  
24 It is an advantageous feature of the invention that the decoding complexity of the  
25 unit rank beamforming scheme is independent of the number of transmit antennas.  
26 Since there is a single stream of data (corresponding to the eigen channel with the  
27 best eigen value) the resulting encoder is a scalar encoder and hence independent of  
28 the number of transmit antennas. As a result, the corresponding decoder is also a  
29 scalar decoder and hence the decoding complexity is independent of the number of  
30 the transmit antennas. In contrast, space time codes encode across all the transmit

1 antennas in a joint fashion, thus resulting in a vector encoder whose order is given by  
 2 the number of transmit antennas. In such a case, the corresponding vector decoder's  
 3 complexity is exponential in the number of transmit antennas.

4 Consider the example of a finite size beamformer codebook given by  $C = \{C_1, C_2, \dots,$   
 5  $C_N\}$ . We can show that the quantizer which minimizes the outage probability is  
 6 given by

$$\min_{C_i \in C} \|HC_i^\dagger\|_2^2, \quad (2)$$

7  
 8 where  $\|\cdot\|_2$  represents the  $l_2$  norm on  $\mathbb{C}^t$ . Hence, a given channel realization  $H$  will  
 9 be mapped to the beamforming vector  $C_i$  which minimizes expression (2). It can also  
 10 be shown that as  $N$  gets large, the quantization rule given by (2) leads to the  
 11 dominant eigenvector of the channel. This follows from the Rayleigh quotient, which  
 12 states that  $\|HV\|_2$  is maximized when  $V$  is the dominant eigenvector of  $H^\dagger H$ .

13  
 14 We can further establish a lower bound on the outage performance of the unit rank  
 15 beamforming scheme when the beamforming codebook size is constrained to  $N=2^B$   
 16 vectors. In particular, for  $t$  transmit antennas and  $r=2$  receive antennas, we can show  
 17 that the outage probability of the system is bounded below as follows:

$$P_{\text{out}}(R, P) \geq 1 - N(1 + \gamma_0)e^{-\gamma_0} + e^{-\gamma_1} \left( \sum_{k=0}^{2t-1} \frac{N(1 + \gamma_0)(\gamma_1 - \gamma_0)^k - \gamma_1^k}{k!} \right) - Ne^{-\gamma_1} \gamma_0 \frac{(\gamma_1 - \gamma_0)^{2t-1}}{(2t-1)!} \quad (3)$$

19

20



1 Where  $\gamma_0 = \frac{2^R - 1}{P}$  and  $\gamma_1$  is a function of  $N$ ,  $t$  and  $\gamma_0$ .

2 Hence, with the above quantization rule, all the beamformer constructions which  
 3 were known for a single receive antenna can be adapted for multiple receive  
 4 antennas also. The design criterion for good beamformer codebooks in the case of  
 5 single receive antenna is therefore given by

$$\min_c \max_{i,j:i \neq j} |\langle C_i, C_j \rangle|. \quad (4)$$

6

7

8 Under appropriate circumstances, the above design criterion is mathematically  
 9 equivalent to the design criterion of unitary space time constellations for non-  
 10 coherent constellations. Hence, all the constructions available for unitary  
 11 constellation design can also be used for the beamformer design problem with the  
 12 quantization metric given by (2).

13 Figure 2 shows the performance of the quantized unit rank beamformers with four  
 14 transmit antennas and two receive antennas transmitting at  $R=2$  bits/sec/Hz (curves  
 15 104 and 106). The performances of a space-time coding scheme which does not use  
 16 any channel state information (curve 110) as well as the spatial water-filling solution  
 17 which requires complete channel state information (curve 102) are also given for  
 18 comparison. With 6 bits of feedback information (curve 106), we see a gain of over  
 19 2.5 dB for the unit rank beamforming scheme over the space time coding scheme at  
 20 an outage performance of  $10^{-2}$ . The gains increase further as the number of feedback  
 21 bits is increased. Note that we can potentially gain up to 4dB over space time codes  
 22 using unit rank beamforming schemes. Further, the gap between the unit rank  
 23 beamforming scheme (curve 104) and the higher rank water-filling scheme (curve  
 24 102) is less than 0.4dB for this rate of transmission. The performance gains are in  
 25 addition to significant reduction in complexity for the beamforming scheme over the  
 26 space time coding as already explained. Further, the performance of dominant

1 eigenvector beamforming (curve 104) which is the limit of the unit rank  
2 beamforming as the number of beamforming vectors gets large is also given in  
3 Figure 2.

4 In the next section, we will present higher rank beamforming schemes (spatial water-  
5 filling) with finite rate feedback, which provide significant performance gains over  
6 space time codes as well as unit rank beamforming schemes when the transmission  
7 rate is increased (in particular, when  $2^{R/t} / t < 1$ , where  $R$  is the rate of transmission,  $r$   
8 is the number of receive antennas and  $t$  is the number of transmit antennas).

9

10 We now propose an algorithm to extend the unit rank beamforming approach for  
11 multiple receive antennas to a quantized spatial water-filling approach for the case of  
12 two receive antennas. The algorithm can be easily extended to the case of more than  
13 two receive antennas. Next generation handsets are expected to be equipped with no  
14 more than two antennas, due to size and cost constraints. Hence, the case of two  
15 receive antennas is important for downlink transmission in cellular systems.

16

17 For the case of a spatial water-filling solution, the transmitter needs to possess  
18 information about the eigenvectors as well as the eigenvalues of  $H^H H$ . Note that  
19 the knowledge of the relative value of the eigenvalues (e.g. ratio of the eigenvalues)  
20 will not suffice for the water-filling power allocation. The invention employs a  
21 quantizer solution in which the eigenvectors and the power allocation vector are  
22 quantized independently. This separation imposes certain structure on the quantizer  
23 design, which advantageously reduces the complexity of implementation of the  
24 quantizer in practice.

25 In the case of two receive antennas ( $r = 2$ ),  $H^H H$  can at most have two non-zero  
26 eigenvalues. Hence, the knowledge at the transmitter should comprise these two  
27 eigenvectors (corresponding to non-zero eigenvalues) as well as the corresponding  
28 eigenvalues. The inventors have realized that significant savings in feedback

1 resources can be obtained if the power allocation is made at the receiver and the  
2 information about the power distribution in the two eigen channels is passed back to  
3 the transmitter. Further, there is no loss in information if the power distribution  
4 vector  $P_1, P_2$  is normalized to unity since the total power available ( $P$ ) is known at  
5 the transmitter. Hence, we can design a computationally simple quantizer for the  
6 power allocation vector. Further, we have observed that a 2 bit quantizer effectively  
7 conveys all the information required for the power allocation at the transmitter.  
8 Additionally, we can gain up to one bit in feedback resources by noting that  $P_1$   
9 corresponding to the dominant eigenvector is always greater than or equal to  $P_2$   
10 corresponding to the other eigen channel. The quantizer for the power distribution  
11 vector is given in Table 1. Note that we set  $P_2 = k P_1$ , where  $0 \leq k \leq 1$ , with  $P_1 \geq 0.5P$   
12 , where 2 bits are used to describe  $k$ .

13

14

Table 1: Quantizer used for the power allocation vector in the case of 4 transmit antennas and 2 receive antennas.

Water-filling solution	k
$0.75 \leq \frac{P_2}{P_1} \leq 1$	1
$0.5 \leq \frac{P_2}{P_1} \leq 0.75$	$\frac{1}{2}$
$0.25 \leq \frac{P_2}{P_1} \leq 0.5$	$\frac{1}{5}$
$0 \leq \frac{P_2}{P_1} \leq 0.25$	0

The effect of quantizing the power allocation vector to 2 bits as given in Table 1 can be seen in Figure 3 for the case of 4 transmit antennas and 2 receive antennas. We assume that the eigenvectors are known perfectly at the transmitter for this simulation to study the effects of quantization of the power allocation vector. Figure 3 shows the result of a two bit quantizer configured with perfect channel information. It can readily be seen that the two curves are essentially identical, so that the performance loss of the 2 bit power quantizer is negligible compared to the case of perfect channel state information.

We will now discuss the quantization of the two active eigenvectors of  $H^H H$ . Consider a finite size beamformer codebook  $\mathcal{C}$  of size N constructed as described in the previous section. We can first apply the quantization rule introduced in the last section to determine the best approximation to the dominant eigenvector among the

1 available vectors in  $\mathcal{C}$ . Note that the specification of this vector at the transmitter  
 2 requires  $\log_2(N)$  feedback bits. However, we can gain substantially in the  
 3 specification of the second eigenvector by noting the following useful property.

4 Note that the eigenvectors of  $H^H H$  lie in  $\mathbb{C}^t$ . Further, the eigenvectors are all  
 5 mutually orthogonal. Hence, the specification of the first eigenvector determines the  
 6 subspace which contains the second active eigenvector. In particular, the second  
 7 eigenvector lies in the  $t-1$  dimensional subspace which is orthogonal to the principal  
 8 eigenvector. Hence, we can improve the description of the second vector  
 9 significantly by constructing a second codebook in  $t-1$  dimensions instead of the  
 10 original  $t$  dimensional space.

11 However, it is not desirable to modify the composition of the codebook of the second  
 12 eigenvector based on the first eigenvector, since the orthogonal subspace containing  
 13 the second vector depends on the principal eigenvector. We therefore present an  
 14 algorithm where both the beamformer codebooks are independent of the actual  
 15 channel realization.

16  
 17 Let  $C_1$  be a beamformer codebook in  $\mathbb{C}^t$  comprising of  $N_1=2^{B_1}$  vectors. Similarly, let  
 18  $C_2$  be a beamformer codebook in  $\mathbb{C}^{t-1}$  comprising of  $N_2=2^{B_2}$  vectors. Let  $H$  be the  
 19 channel realization, while  $V_1$  and  $V_2$  are the active eigenvectors of  $H^H H$ .

20 We first quantize  $V_1$  in  $C_1$  using the quantization rule discussed in the last section. In  
 21 particular, we pick  $C_i^1 \in C_1$  (note that the superscript corresponds to the codebook  
 22 index) such that  $\|H(C_i^1)^H\|_2$  is the maximum for all the vectors in  $C_1$ . Without loss of  
 23 generality, we assume that  $C_1^1$  maximizes the inner product with  $H$  among all the  
 24 vectors in  $C_1$ .

25 Now, consider the vectors in  $C_2$ . We construct a codebook  $C_2'$  from  $C_2$  such that  $C_2'$   
 26 lies in  $\mathbb{C}^t$ . Hence,  $C_2$  is an embedding of  $C_2'$  in  $\mathbb{C}^{t-1}$ . By construction,  $C_2'$  is such  
 27 that the first co-ordinate of all the vectors is set to zero. Hence, the vectors in  $C_2'$  lie

1 in the orthogonal subspace of the axis  $[1, 0, \dots, 0]$  of  $\mathbb{C}^t$ . Further, the embedding rule  
2 of  $C_2'$  into  $C_2$  is that the first co-ordinate of  $C_2'$  is dropped to obtain the  
3 corresponding vector in  $C_2$ . Hence, if  $C_i^{2'} = [0, c_1, c_2, \dots, c_{t-1}]$ , then the corresponding  $C_i^{2'}$   
4 in  $C_2$  is given by  $[c_1, c_2, \dots, c_{t-1}]$ .

5 Now, we make use of the property that  $C_2'$  is in the orthogonal subspace of  
6  $e_1 = [1, 0, \dots, 0]$  in  $\mathbb{C}^t$ . In particular, we rotate the vectors in  $C_1$  such that  $C_1^1$  coincides  
7 with  $e_1$ . Let  $A$  be a  $t \times t$  unitary matrix, constructed in a predetermined fashion from  
8  $C_1^1$  such that  $AC_1^1 = e_1$ . Now, we rotate the channel matrix  $H$  by the same matrix  $A$   
9 before we quantize the second vector. Equivalently, we rotate the second vector  $V_2$   
10 by the matrix  $A$  to give  $V_2' = AV_2$ . Now, we quantize  $V_2'$  in the second beamformer  
11 codebook  $C_2^{2'}$ . Suppose  $C_k^{2'}$  is the vector in  $C_2^{2'}$  which maximizes the inner product  
12 with  $V_2'$ . Then, the transmitter gets the label  $k$  and the transmitter uses  $A(C_2')^T$  for  
13 transmission, where the superscript  $T$  stands for matrix transpose operation. Note  
14 that  $A$  is a function of  $C_1^1$  only and since the transmitter has information about  $C_1^1$   
15 via the feedback channel, the matrix  $A$  can be reproduced at the transmitter. Hence,  
16 both the resulting codebooks,  $C_1$  and  $C_2$  are independent of the actual channel  
17 realization.

18

Table 2: Table showing the decoding complexity as a function of the number of transmit antennas ( $t$ ), receive antennas ( $r$ ) and number of points in the modulation constellation ( $|Q|$ ).

Transmission scheme	Decoding complexity
Space time coding	$\propto r Q ^t$
Unit rank beamforming	$\propto r Q $
Spatial water-filling	$\propto r Q ^{\min(t,r)}$

1

2 Note that the quantized spatial water-filling solution requires joint coding and  
3 decoding across the active eigen channels. Hence, in the case of four transmit and  
4 two receive antennas which results in two active eigen channels, we will need joint  
5 coding across the two eigen channels. For instance, space time coding of rank 2  
6 could be used to achieve the performance depicted in the next section. In the absence  
7 of channel state information, we would require a space time code of rank 4  
8 corresponding to the four transmit antennas. Note that the decoding complexity of  
9 space time codes is exponential in the rank of the code. Hence, the quantized spatial  
10 water-filling solution results in significantly lower decoding complexity compared to  
11 the space-time coding, in addition to the benefits obtained in performance gains. The  
12 dependence of the decoding complexity on the number of transmit antennas and the  
13 number of receive antennas is shown in Table 2.

14 The performance of the quantized water-filling solution with 4 transmit antennas and  
15 2 receive antennas is given in Figure 3. The figure shows the performance of a  
16 quantized water-filling scheme in comparison with the perfect information water-  
17 filling scheme, space time coding and perfect information eigenvector beamforming,  
18 all transmitting at the rate of  $R=6$  bits/sec/Hz. For the quantized beamforming  
19 scheme, we have used 2 bits for spatial power control information, using the  
20 quantizer given in table 1. We observe the performances of two different codebook  
21 constructions in Figure 3. In the first case, the codebook  $C_1$  was constructed in 4  
22 dimensions with 16 vectors while the codebook  $C_2$  was constructed in 3 dimensions  
23 with 16 vectors, thus requiring 3 feedback bits for each codebook. Hence, a total of  
24 10 bits of feedback was used for this scheme. With 10 feedback bits, we note that we  
25 are just about 1 dB away from perfect feedback information while we obtain a gain  
26 of about 2 dB over space time coding. For the case of 8 feedback bits, we use 2 bits  
27 for spatial power control. Again,  $C_1$  is in 4 dimensions, now with 8 vectors, while  $C_2$   
28 is in 3 dimensions with 8 vectors, thus requiring 3 bits each. With 8 feedback bits,

1 we observe a gain of about 1.5 dB over the space time coding scheme. It should also  
2 be pointed out that the unit rank beamforming scheme performs worse than the space  
3 time code in this case.

4  
5 The beamforming schemes for multiple transmit and receive antenna systems  
6 presented above apply when only partial channel state information is available at the  
7 transmitter. The unit rank beamforming solution results in a low complexity  
8 decoding structures as well as performance gains over channel agnostic space time  
9 coding schemes. An algorithm for implementing higher rank transmission schemes,  
10 such as a spatial water-filling solution, using low complexity quantizers has also  
11 been illustrated. In all the cases, a few bits of channel state information at the  
12 transmitter can lead to substantial performance gains as well as reduction in  
13 decoding complexity.

14  
15 In the next-section, we will show that the design of good beamformers for a multiple  
16 transmit and a single receiver system can be posed as the design of unitary space  
17 time constellations. The design of the unitary space time constellation is a dual  
18 problem of the design of good beamformers with the coherence time in the case of  
19 the unitary space time constellation given by the number of transmit antennas in the  
20 case of the beamformer design problem. Also, the number of transmit antennas in the  
21 equivalent unitary space time constellation design problem is set to unity (which is  
22 the number of receive antennas for the beamforming problem). We will establish the  
23 equivalence in the sequel and demonstrate the hitherto unknown use of unitary space  
24 time constellation as a beamformer with the help of an example. We will use the  
25 lower bound outage performance of beamformers for evaluating the performance of  
26 the unitary space time constellation as a beamformer.

27  
28 Unitary space time constellations for multiple antenna systems were introduced by  
29 Marzetta and Hochwald in "Capacity of a mobile multiple-antenna communication



link in rayleigh flat fading", IEEE Transactions on Information Theory, pp 139 –  
 157, January, 1999. In particular, they showed that the unitary space time  
 constellations achieve the capacity of multiple antenna systems when the channel  
 information is not available at both the transmitter and the receiver. The design  
 criterion for unitary space time constellations to minimize the probability of pair-  
 wise error probability was given in "Unitary space-time modulation for multiple-  
 antenna communications in rayleigh flat fading", IEEE Transactions on Information  
 Theory, vol 46, pp. 543-564, March 2000. A unitary space time constellation consists  
 of signals  
 $V_1, V_2, V_3, \dots, V_N$  where  $V_i \in \mathbb{C}^{T \times M}$ . Here T is the block length of the code (less than or  
 equal to the coherence time of the channel) and M has the interpretation of number  
 of transmit antennas. Also,  $V_i^\dagger V_i = I$  for each i, for unitarity. It was shown that the  
 design criterion for good unitary space time constellations is to minimize  $\delta$ , where  
 $\delta$  is defined as

$$\delta = \max_{1 \leq l < l' \leq N} \|\Phi_l^\dagger \Phi_{l'}\|, \quad (1)$$

where the norm used above is a scaled Frobenius norm of a matrix, the scaling factor  
 being given by M in this case.

Now consider the design of a good beamformer comprising N vectors for a system  
 with n transmit antennas and a single receive antenna. It can be shown that the  
 design criterion for good beamformers is

$$\min_c \max_{1 \leq l < l' \leq N} |\langle C_l, C_{l'} \rangle|, \quad (2)$$

1 where  $C_i \in \mathbb{C}^N$ . The design criterion for unitary space time constellations given in  
 2 (1) reduces to the design criterion of beamformers given in (2), if we set  $T=n$  and  
 3  $M=1$  in (1). We see an equivalence between coherence time, in the unitary  
 4 constellation design problem, and the number of transmit antennas, in the  
 5 beamforming design problem.

6

7 Systematic unitary space time constellation as beamformer

8 The design criterion for beamformers which was introduced in the previous section  
 9 is quite general and an exhaustive computer search can be used to construct a good  
 10 beamformer containing a given number of beamforming vectors. We now look at a  
 11 particular way of designing these beamformers, viz., using a Fourier based approach  
 12 for unitary space time constellations. Hochwald et al. in "Systematic design of  
 13 unitary space-time constellations" IEEE Transactions on Information Theory, vol.  
 14 46, pp. 1962-1973, September 2000, considered the problem of imposing structure  
 15 on the unitary space time constellations for easier encoding/decoding as well as to  
 16 reduce the dimensionality of the search space during the design process. The  
 17 equivalence of good beamformers with good unitary space time constellations  
 18 established in the previous section reveals the hitherto unknown properties of the  
 19 systematic constructions. We will show that the unitary space time constellations  
 20 designed by Hochwald et al. The cited reference serve as good beamformers for the  
 21 dual problem with the new meaning of the number of transmit antennas attached to  
 22 coherence time as discussed above.

23 Consider the set of linear block codes defined by the  $K \times T$  generator matrix  $U$ ,  
 24 whose elements are in  $R_q$ , ring of integers modulo- $q$ . The code  $\mathcal{C}$  represented by  $U$   
 25 comprises codewords  $C_l$  given by  $C_l = lU$ , where  $l$  is a  $1 \times K$  vector with elements  
 26 taken from  $R_q$ . Thus, the size of the codebook is given by  $|\mathcal{C}| = q^K$ . The codewords  
 27 are mapped into signals by mapping the integers in the codeword into components of  
 28 a complex signal via the transformation

$$\phi(j) = \frac{1}{\sqrt{T}} e^{i \frac{2\pi}{q} j}, j = 0, 1, \dots, q-1. \quad (3)$$

Finally, the unitary space time constellation is given by

$$\Phi_l = \phi(C_l) \quad (4)$$

$$= \frac{1}{\sqrt{T}} \begin{bmatrix} e^{i \frac{2\pi}{q} [C_l]_1} \\ e^{i \frac{2\pi}{q} [C_l]_2} \\ \vdots \\ e^{i \frac{2\pi}{q} [C_l]_T} \end{bmatrix}, 1 \leq l \leq N$$

Suppose, we wish to design a beamformer comprising of  $N=16$  vectors for  $n=8$  transmit antennas transmitting at 2 bits/sec/Hz and a single receive antenna. Then the corresponding dual problem of designing unitary space time constellation reduces to designing a codebook of size  $N=16$  with a single transmit antenna (i.e.,  $M=1$ ) and coherence time given by  $T=8$ . One of the codes designed for this problem in the cited reference is characterized by  $U=[1 \ 0 \ 3 \ 14 \ 15 \ 11 \ 10 \ 8]$ ,  $K=1$  and  $q=16$ .

The performance of this beamformer is given in Figure 5. The rate of transmission is  $R=2$  bits/sec/Hz. The corresponding performance predicted by the lower bound on outage is also given in the figure. It can be seen that the performance of the constructed beamformer comes very close (less than 0.05dB away) to the corresponding lower bound on outage probability. The performance of space time codes, which do not require any feedback information, is also given in the plots for reference. Note that there is gain of about 4dB with 4 bits of feedback compared to the space time codes. It should also be noted that there will be gains from reduced

1 receiver complexity also from the beamforming schemes which are not quantified in  
2 this document.

3 A similar construction taken from the cited reference again for  $n=8$  transmit antennas  
4 and  $N=64$  beamforming vectors is given in Figure 6. The unitary space time  
5 constellation in this case is characterized by  $N=64$ ,  $T=8$ ,  $K=3$ ,  $q=4$  and  $U = [I_3 \ U']$ ,  
6 where  $I_3$  is the  $3 \times 3$  identity matrix and  $U'$  is given by

$$U' = \begin{bmatrix} 2 & 3 & 3 & 3 & 0 \\ 2 & 0 & 3 & 1 & 1 \\ 0 & 3 & 2 & 3 & 3 \end{bmatrix} \quad (5)$$

7  
8  
9 For the case of 64 beamforming vectors, we present another straight-forward  
10 beamforming scheme for comparison. We use 1 bit to quantize the phase information  
11 of each one of the channel coefficients, leading to 8 bits in all, for 8 channel  
12 coefficients. The performance of this beamformer is also plotted in Figure 6. It can  
13 be seen that the performance of the constructed beamformer is again less than  
14 0.05dB away from the corresponding bound. Further, the gain compared to the  
15 space time coding scheme now increases to about 6 dB. It can be observed from the  
16 plot there is lot of gain compared to the phase quantization scheme also. This shows  
17 that the systematic unitary space time constellations serve as very good  
18 beamformers. Some more constructions of the beamformers for  $n=8$  transmit  
19 antennas can be obtained from the cited reference for the cases of  $N=133$ , 256, 529,  
20 1296 and 2209 vectors.

## WE CLAIM:

- 1 1. A method of forming a beam of a signal to be transmitted from a base station transceiver  
2 in a communication system having a communication channel between a base station and a  
3 mobile station and a return channel for data transmitted from the mobile station to the base  
4 station, the method comprising:  
5  
6 Providing a codebook ( C ) of parameters that modify a transmitted signal;  
7 Providing a channel matrix ( H ) of parameters representing the properties of the channel;  
8 transmitting a signal from the base station along a channel using an antenna comprising at  
9 least two elements;  
10 Receiving said transmitted signal in said mobile station and estimating a parameter in the  
11 channel matrix characteristic of the channel by selecting the value of a parameter in the  
12 codebook that minimizes a criterion;  
13 transmitting an indication of the selected parameter over the return channel and  
14 applying the codebook vector associated with the selected parameter to subsequent transmissions  
15 from the base station.
- 1 2. A method according to claim 1, in which an eigenvector of said channel matrix is  
2 provided by a calculation based on said parameter.
- 1 3. A method according to claim 2, in which said calculation is performed in said mobile  
2 station.
- 1 4. A method according to claim 1, in which said base station transmits a set of initial setup  
2 signals that are used by the mobile station to estimate the parameters of the channel.
- 1 5. A method according to claim 4, in which an eigenvector of said channel matrix is  
2 provided by a calculation based on said parameter.
- 1 6. A method according to claim 5, in which said calculation is performed in said mobile  
2 station.
- 1 7. A method according to claim 1, in which the signal is divided into frames and the process  
2 of estimating a parameter, transmitting an indication of the selected parameter and applying the  
3 codebook vector is repeated for each frame.
- 1 8. A method according to claim 7, in which an eigenvector of said channel matrix is  
2 provided by a calculation based on said parameter.
- 1 9. A method according to claim 8, in which said calculation is performed in said mobile  
2 station.

- 1 10. A method according to claim 1, in which said base station transmits a set of initial setup  
2 signals that are used by the mobile station to estimate the parameters of the channel.
- 1 11. A method according to claim 10, in which an eigenvector of said channel matrix is  
2 provided by a calculation based on said parameter.
- 1 12. A method according to claim 11, in which said calculation is performed in said mobile  
2 station.
- 1 13. A method of forming a beam of a signal to be transmitted from a base station transceiver  
2 in a communication system having a communication channel between a base station and a  
3 mobile station having two antennas and a return channel for data transmitted from the mobile  
4 station to the base station, the method comprising:  
5  
6 Providing a codebook ( C ) of parameters that modify a transmitted signal:  
7 Providing a channel matrix ( H ) of parameters representing the properties of the channel;  
8 transmitting a signal from the base station along two eigenvectors of a channel, the power  
9 allocation between said two eigenvectors being quantized independently from the  
0 quantization of the eigenvectors.
- 1 14. A method according to claim 13, in which the quantization of the power allocation is  
2 performed at the receiver.
- 1 15. A method according to claim 13, in which  $P_1 = kP_2$ , where  $0 \leq k \leq 1$ ,  $P_1$  is  
2 the power in the dominant eigenvector and k is selected from the group comprising 1,  $\frac{1}{2}$ ,  $\frac{1}{5}$ , and  
3 0 when  $R = \frac{P_2}{P_1}$  is correspondingly  $\geq 0.75$ ,  $0.5 < R < 0.75$ ,  $.25 < R < 0.5$  and  $0 < R < .25$ .
- 1 16. A method according to claim 13, in which the dominant eigenvector is quantized by  
2 calculating the eigenvector in the relevant codebook that maximizes  $\|H(C_i^t)^*\|_2$ .
- 1 17. A method according to claim 16, in which the second of two eigenvectors is calculated by  
2 finding that vector in an orthogonal subspace to the first eigenvector that maximizes the inner  
3 product with a beamformer codebook in the orthogonal subspace to the first codebook.
- 1 18. A method according to claim 16, in which the quantization of the power allocation is  
2 performed at the receiver.
- 1 19. A method according to claim 16, in which which  $P_1 = kP_2$ , where  $0 \leq k \leq 1$ ,  $P_1$  is  
2 the power in the dominant eigenvector and k is selected from the group comprising 1,  $\frac{1}{2}$ ,  $\frac{1}{5}$ , and  
3 0 when  $R = \frac{P_2}{P_1}$  is correspondingly  $\geq 0.75$ ,  $0.5 < R < 0.75$ ,  $.25 < R < 0.5$  and  $0 < R < .25$ .

1 20. A method of constructing a beamformer comprising the steps of:  
2 Providing a unitary space-time constellation of at least one signal  $s_i$  having a coherence time  $T$   
3 and one transmit antenna and applying the constellation as a set of at least one beamforming  
4 vectors in an array of  $T$  antennas.

1 21. A method according to claim 20, in which said set of at least one functions have the form

2 
$$V_i = \frac{1}{\sqrt{n}} \exp\left(\frac{i2\pi j}{N}\right) \text{ where } j = 0, 1, 2, \dots, N-1..$$

1 22. A method of constructing a beamformer of  $N$  vectors comprising the steps of:  
2 Providing a transmitter system having  $n$  transmit antennas;  
3 Forming a set of  $N$  functions in a unitary space time constellation with one antenna and a  
4 coherence time of  $n$ ; and  
5 Applying said set of  $N$  functions as a set of  $N$  beamforming vectors.

1 23. A method according to claim 22, in which said set of  $N$  functions have the form

2 
$$V_i = \frac{1}{\sqrt{n}} \exp\left(\frac{i2\pi j}{N}\right) \text{ where } j = 0, 1, 2, \dots, N-1..$$

1 24. A method according to claim 20, of forming a beam of a signal to be transmitted  
2 from a base station transceiver in a communication system having a communication  
3 channel between a base station and a mobile station and a return channel for data  
4 transmitted from the mobile station to the base station, the method comprising:  
5  
6 Providing a codebook (  $C$  ) of parameters that modify a transmitted signal according to  
7 claim 20:  
8 Providing a channel matrix (  $H$  ) of parameters representing the properties of the channel;  
9 transmitting a signal from the base station along a channel using an antenna  
10 comprising at least two elements;  
11 Receiving said transmitted signal in said mobile station and estimating a parameter in the  
12 channel matrix characteristic of the channel by selecting the value of a parameter in the  
13 codebook that minimizes a criterion; transmitting an indication of the selected parameter  
14 over the return channel and  
15 applying the codebook vector associated with the selected parameter to subsequent  
16 transmissions from the base station.  
17



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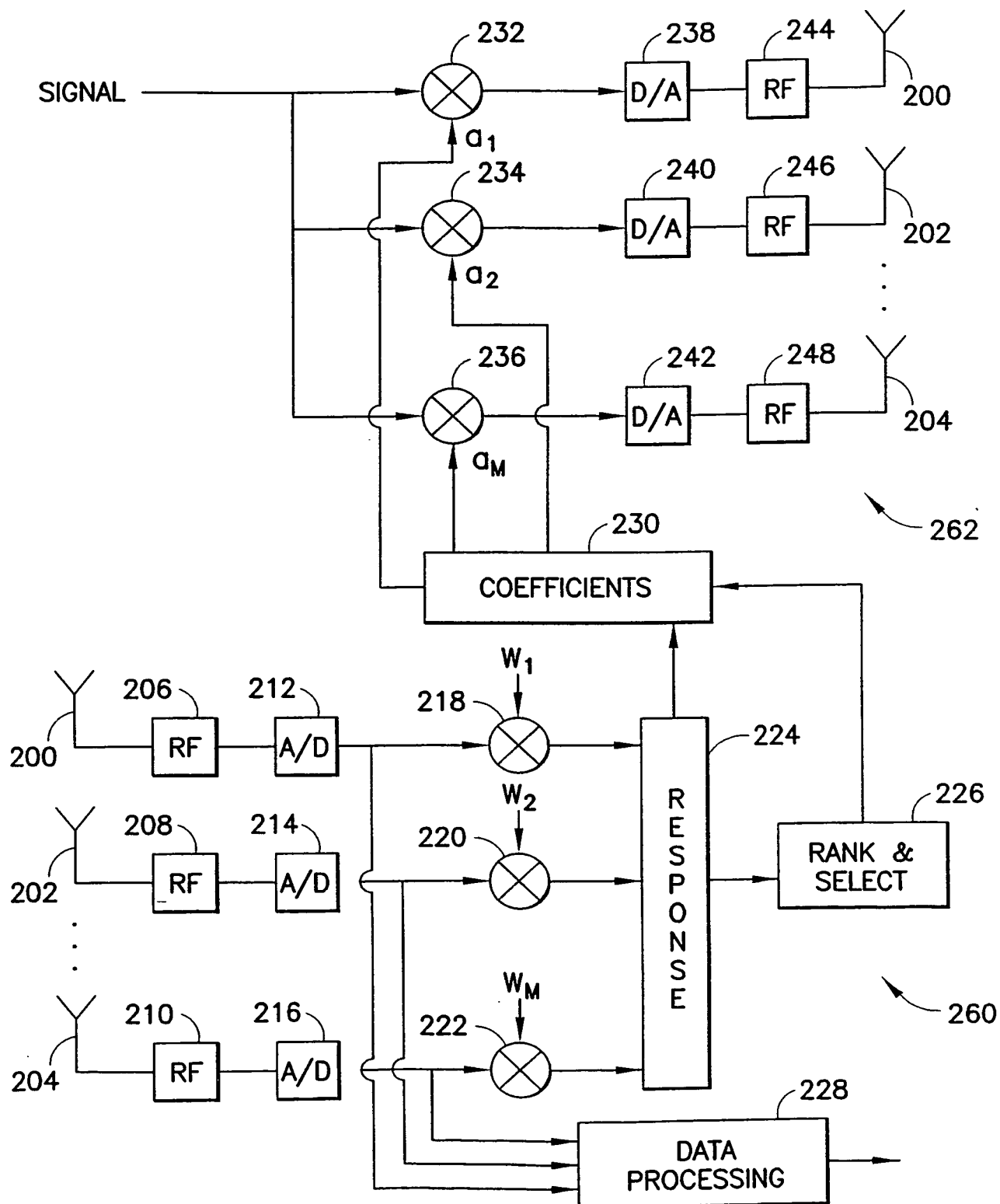


FIG. 1

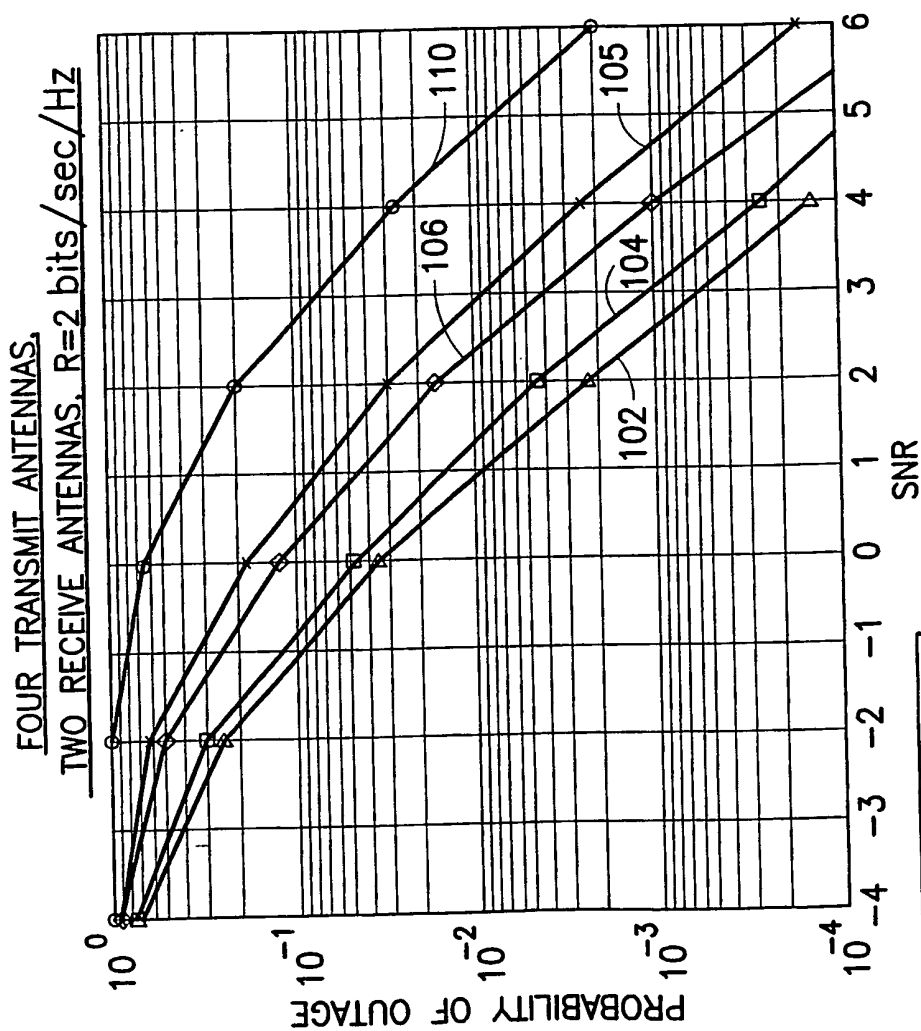


FIG. 2

WATER FILLING  
 DOMINANT EIGEN VALUE  
 6 BITS QUANTIZED BEAMFORMING  
 4 BITS QUANTIZED BEAMFORMING  
 SPACE TIME CODING

▲  
 ■  
 ○  
 ◆  
 ×

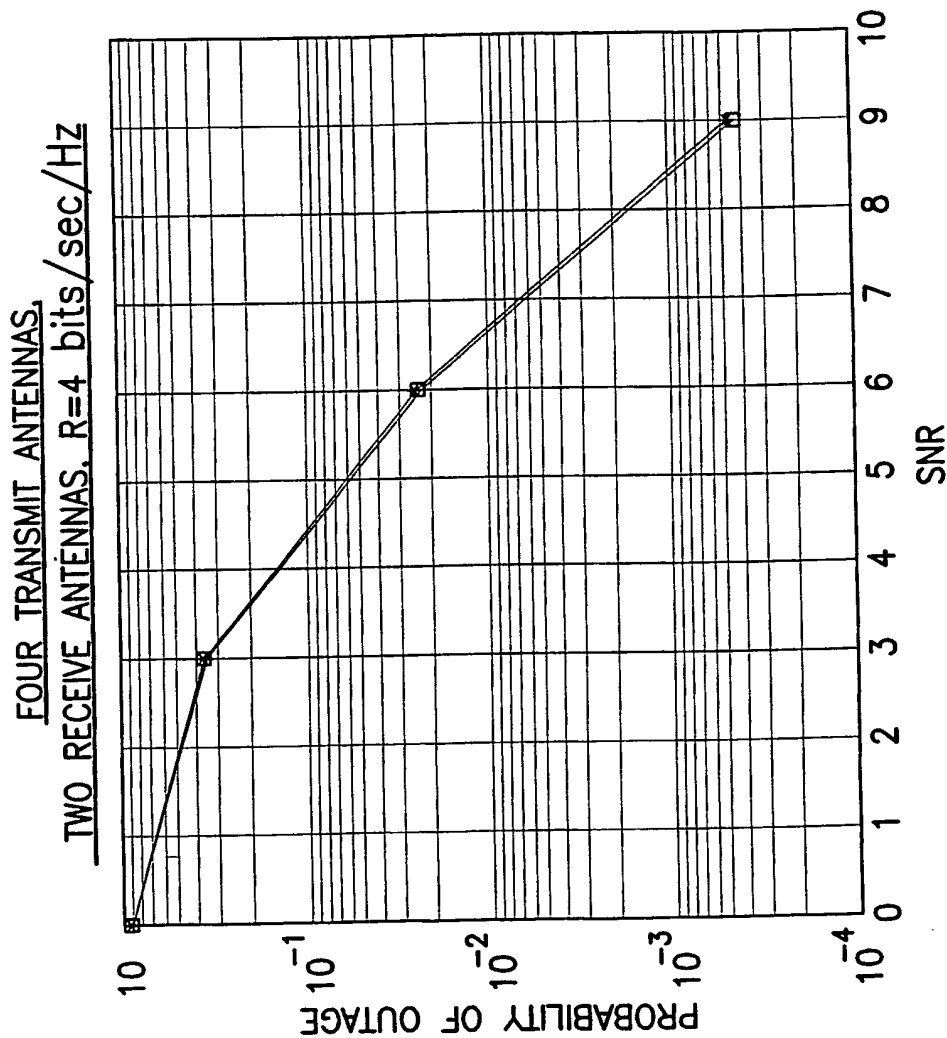
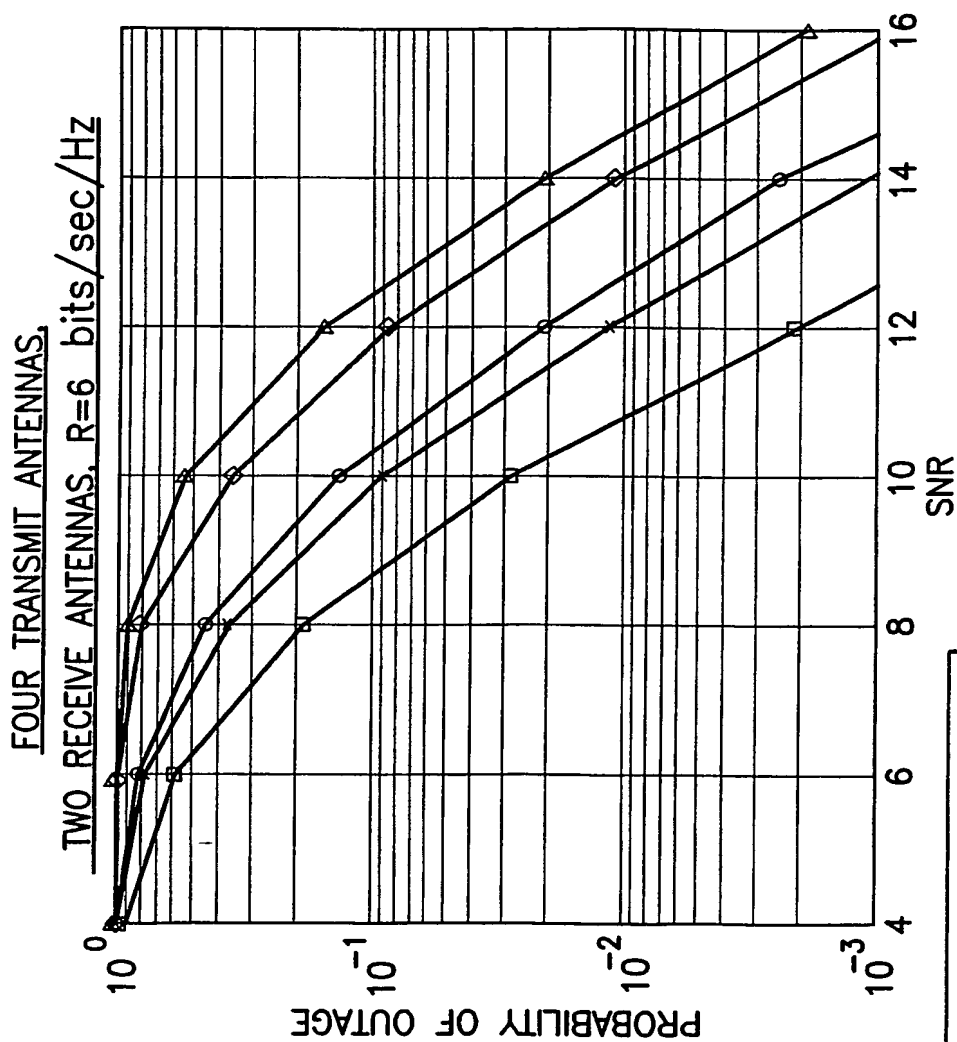


FIG.3

-□- SPATIAL WATER-FILLING WITH PERFECT CSIT  
 -+- POWER ALLOCATION QUANTIZED TO 2 BITS

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- WATER-FILLING
- \* QUANTIZED WATER-FILLING 10 FEEDBACK BITS
- QUANTIZED WATER-FILLING 8 FEEDBACK BITS
- ◇ SPACE TIME CODING
- △ DOMINANT EIGENVECTOR

FIG.4

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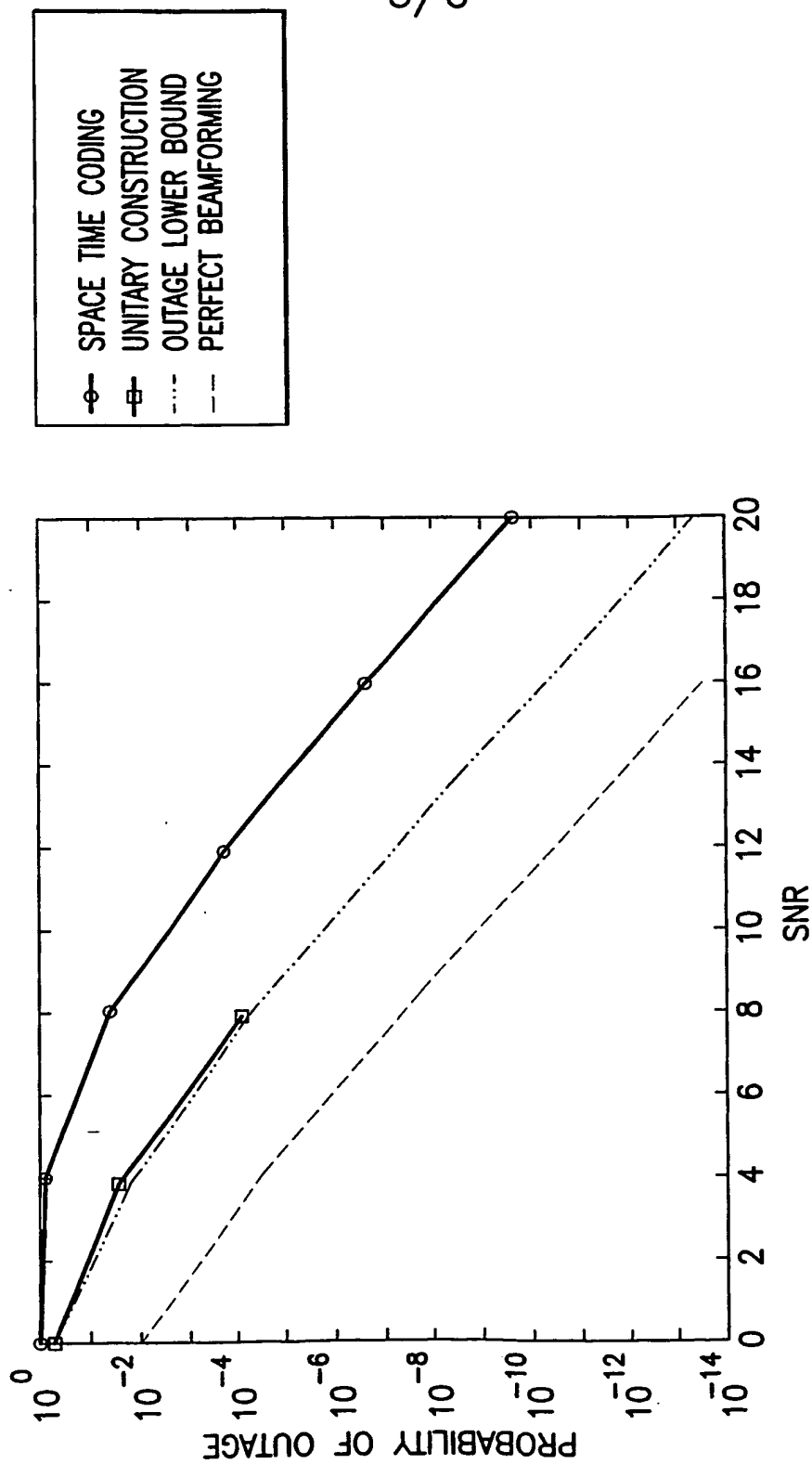


FIG. 5

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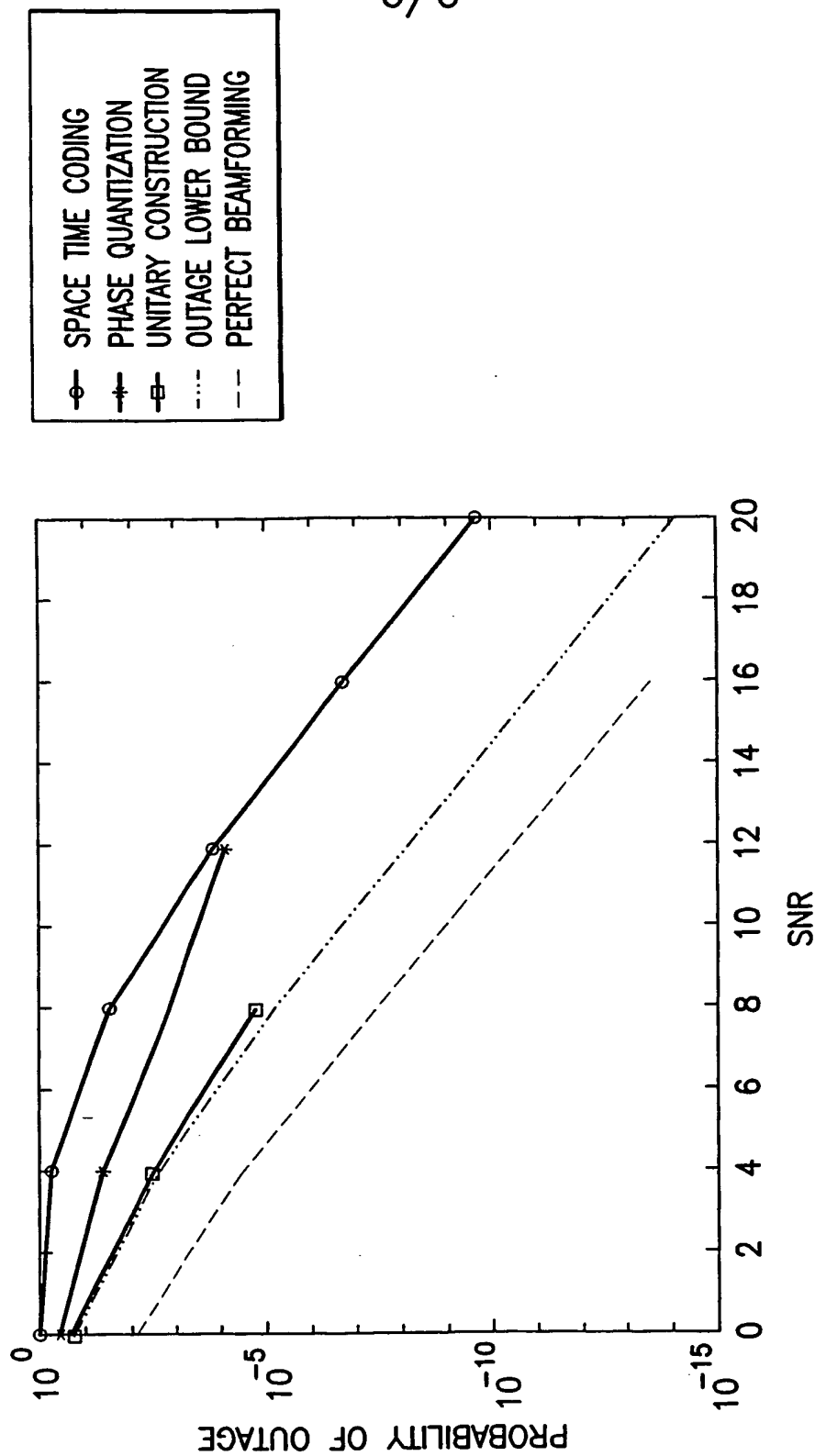


FIG.6

(19) World Intellectual Property  
Organization  
International Bureau



PCT

(10) International Publication Number  
**WO 2004/040690 A3**

(43) International Publication Date  
13 May 2004 (13.05.2004)

(51) International Patent Classification<sup>7</sup>: **H04B 7/14**,  
1/02, 7/02

(21) International Application Number:  
PCT/US2003/034414

(22) International Filing Date: 29 October 2003 (29.10.2003)  
English

(25) Filing Language: English

(26) Publication Language:

(30) Priority Data:  
60/422,277 29 October 2002 (29.10.2002) US

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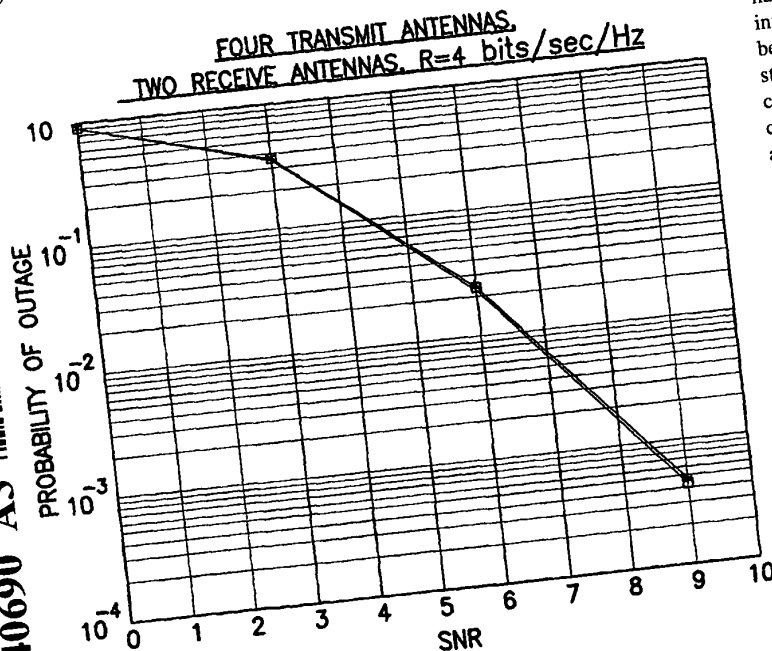
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(81) Designated States (national): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States (regional): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW),  
[Continued on next page]

(54) Title: LOW COMPLEXITY BEAMFORMERS FOR MULTIPLE TRANSMIT AND RECEIVE ANTENNAS



—□— SPATIAL WATER-FILLING WITH PERFECT CSIT  
—+— POWER ALLOCATION QUANTIZED TO 2 BITS

(57) Abstract: Beamforming systems having a few bits of channel state information fed back to the transmitter benefit from low complexity decoding structures and performance gains compared with systems that do not have channel state feedback. Both unit rank and higher rank systems are implemented. Substantial design effort may be avoided by following a method of using functions formulated for space-time systems with the change that the channel coherence time is equated to the number of transmit antennas and the number of antennas in the space-time formulation is fixed at one



Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM),  
European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE,  
ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, RO,  
SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM,  
GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

(88) Date of publication of the international search report:

15 July 2004

**Published:**

- with international search report
- before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments

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10/533248

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/US03/34414

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : H04B 7/14, 1/02, 7/02

US CL : 455/561, 25, 101, 103, 70, 130, 137; 375/316, 349

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 455/561, 25, 101, 103, 70, 130, 137; 375/316, 349

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P	US 2003/0185309 A1 (PAUTLER et al) 02 October 2003, see entire document.	1-14 and 24
A	US 2002/0013130 A1 (KIM et al) 31 January 2002, see entire document.	1-24
A,P	US 2004/0033791 A1 (SCHIMDL et al) 19 February 2004, see entire document.	1-24
A,P	US 2003/0181170 A1 (SIM) 25 September 2003, see entire document.	1-24
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Date of the actual completion of the international search

27 April 2004 (27.04.2004)

Date of mailing of the international search report

20 MAY 2004

Name and mailing address of the ISA/US

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